is seen to be spectral green. But in this case the physical stimulus is complex. On adding to the magenta a yellow glass, to cut out the violet, or using candle light, the violet reappears in the complementary spectrum, while if a blue glass is added instead, the violet vanishes, and red stands out brightly in the spectrum. It may be thus shown that the colour which has green for its complementary is not spectroscopically simple, and since the spectral elements of it have each a different and independent effect upon the spectrum of the complementary colour, I conclude that the green sensation has no special connection with the red, or indeed with any single colour sensation.

It would, of course, be easy to arrange the apparatus so as to use pure spectral colours for the backgrounds, but the phenomena are sufficiently distinct for ordinary purposes with coloured glasses.

A portion of the apparatus used has been paid for out of the sum of £10 allotted to me by the Royal Society from the Government Grant.

"An Experimental Investigation into the Flow of Marble." By FRANK D. ADAMS, M.Sc., Ph.D., Professor of Geology in McGill University, Montreal, and JOHN T. NICOLSON, D.Sc., M.Inst.C.E., Head of the Engineering Department, Municipal Technical School, Manchester. Communicated by Professor H. L. CALLENDAR, F.R.S. Received June 12,—Read June 21, 1900.

(Abstract.)

That rocks, under the conditions to which they are subjected in certain parts of the earth's crust, become bent and twisted in the most complicated manner is a fact which was recognised by the earliest geologists, and it needs but a glance at any of the accurate sections of contorted regions of the earth's crust which have been prepared in more recent years to show that there is often a transfer or "flow" of material from one place to another in the folds. The manner in which this contortion, with its concomitant "flowing," has taken place is, however, a matter concerning which there has been much discussion, and a wide divergence of opinion. Some authorities have considered it to be a purely mechanical process, while others have looked upon solution and redeposition as playing a necessary *rôle* in all such movements. The problem is one on which it would appear that much light might be thrown by experimental investigation. If movements can be induced in rocks under known conditions, with the reproduction of the structures found in deformed rocks in nature, much might be learned concerning not only the character of the movements, but also con-

cerning the conditions which are necessary in order that the movements in question may take place.

It is generally agreed that three chief factors contribute to bringing about the conditions to which rocks are subjected in the deeper parts of the earth's crust, where folding with concomitant flowing is most marked. These are:—

1. Great pressure.
2. High temperature.
3. Percolating waters.

With regard to the first factor, it must be noted that mere cubic compression does not produce movements of the nature of flowing, although it may produce molecular rearrangement in the rock. A differential pressure is necessary to give movement to the mass. As Heim has pointed out, there is reason to believe that "Umformung ohne Bruch" takes place when a rock is subjected to a pressure which, while greater in some directions than in others, in every direction exceeds the elastic limit of the rock in question. Whether all these factors, or only certain of them, are actually necessary for the production of rock deformation is a question which also requires to be determined by experiment, for by experiment the action of each can be studied separately, as well as in combination with the others.

In the paper of which this is an abstract, a first contribution to such a study is presented, pure Carrara marble being the rock selected for study. The investigation is now being extended to various other limestones, as well as to granites and other rocks.

In order to submit the marble to a differential pressure, under the conditions above outlined, it was sought to enclose the rock in some metal having a higher elastic limit than marble, and at the same time possessing considerable ductility. After a long series of experiments, heavy wrought-iron tubes of special construction were adopted. These were made, following the plan adopted in the construction of ordnance, by rolling thin strips of Low Moor iron around a bar of soft iron, and welding the strips successively to the bar, as they were rolled around it. The core of soft iron composing the bar was then bored out, leaving a tube of Low Moor iron, the sides being about $\frac{1}{4}$ inch in thickness, and so constructed that the fibres of the iron ran around the tube instead of being parallel to its length. These were found to answer the requirements admirably.

The following procedure was then adopted. Columns of the marble, an inch or in some cases 0·8 inch in diameter and about 1·5 inch in length, were accurately turned and polished. The tube was then very accurately fitted around the marble. This was accomplished by giving a very slight taper to both the column and the interior of the tube, and so arranging it that the marble would only pass half

way into the tube when cold. The tube was then expanded by heating, so as to allow the marble to pass completely into it and leave about 1·25 inch of the tube free at either end. On allowing the tube to cool, a perfect contact between the iron and the marble was obtained. In some experiments the tube was subsequently turned down, so as to be somewhat thinner immediately around the marble. Into either end of the tube, containing the column, an accurately fitting steel plug or piston was then inserted, and by means of these the pressure was applied. The high pressure required was obtained by means of a powerful press, especially constructed for the purpose, consisting of a double hydraulic "intensifier," the water pressure being in the first instance obtained from the city mains. By means of this machine, pressures up to 13,000 atmospheres could be exerted on the columns having a diameter of 0·8 inch, and the pressures could be readily regulated and maintained at a constant value for months at a time, if required.

It having been ascertained that the columns of the marble 1 inch in diameter and $1\frac{1}{2}$ inch in height crushed at a pressure of from 11,430 to 12,026 lbs. to the square inch, the column enclosed in its wrought-iron tube, in the manner above described, was placed in the machine and the pressure applied gradually, the exterior diameter of the tube being accurately measured at frequent intervals. No effect was noticeable until a pressure upon the marble, varying of course with the thickness of the enclosing tube, but generally about 18,000 lbs. to the square inch, was reached; when the tube was found to slowly bulge, the bulge being symmetrical and confined to that portion of the tube surrounding the marble. The distension was allowed to increase until the tube showed signs of rupture, when the pressure was removed and the experiment concluded. The conditions under which the marble was submitted to pressure were four in number:—

1. At the ordinary temperature in the absence of moisture. (Cold dry crush.)
2. At 300° C. in the absence of moisture. (Hot dry crush.)
3. At 400° C. in the absence of moisture. (Hot dry crush.)
4. At 300° C. in the presence of moisture. (Hot wet crush.)

Eight experiments were made on marble columns at the ordinary temperature, in the absence of moisture, the rate at which the pressure was applied differing in different cases, and the consequent deformation being in some cases very slow and in others more rapid, the time occupied by the experiment being from ten minutes to sixty-four days. The amount of deformation was not in all cases equal, as some of the tubes showed signs of rupture sooner than others. On the completion of the experiment the tube was slit through longitudinally by means of a narrow cutter in a milling machine, along two lines

opposite one another. The marble within was found to be still firm and compact, and to hold the respective sides of the tube, now completely severed from one another, so firmly together that it was impossible without mechanical aids to tear them apart. By means of a steel wedge driven in between them, however, they could be separated, but only at the cost of splitting the marble through longitudinally. The half columns of the marble now deformed generally adhere so firmly to the tube that it is necessary to spread the latter in a vice in order to set them free. The deformed marble, while firm and compact, differs in appearance from the original rock in possessing a dead white colour, somewhat like chalk, the glistening cleavage surfaces of the calcite being no longer visible. The difference is well brought out in certain cases owing to the fact that a certain portion of the original marble often remains unaltered and unaffected by the pressure. This when present has the form of two blunt cones of obtuse angle whose bases are the original ends of the columns resting against the faces of the steel plugs, while the apices extend into the mass of the deformed marble and point toward one another. These cones, or rather parabolas of rotation, are developed, as is well known, in all cases when cubes of rock, Portland cement, or cast iron are crushed in a testing machine in the ordinary manner. In the present experiments they seldom form any large portion of the whole mass.

In order to test the strength of the deformed rock, three of the half columns from different experiments, obtained as above described, were selected and tested in compression. The first of these, which had been deformed very slowly, the experiment extending over sixty-four days, crushed under a load of 5350 lbs. per square inch; the second, which had been deformed in $1\frac{1}{2}$ hours, crushed under a load of 4000 lbs. per square inch; while the third, which had been quickly deformed, the experiment occupying only 10 minutes, crushed under a load of 2776 lbs. per square inch. As mentioned above, the original marble, in columns of the dimensions possessed by these before deformation, was found to have a crushing weight of between 11,430 and 12,026 lbs. per square inch. These figures show that, making all due allowance for the difference in shape of the specimens tested, the marble after deformation, while in some cases still possessing considerable strength, is much weaker than the original rock. They also tend to show that when the deformation is carried on slowly the resulting rock is stronger than when the deformation is rapid.

Thin sections of the deformed marble, passing vertically through the unaltered cone and the deformed portion of the rock, were readily made, and when examined under the microscope clearly showed the nature of the movement which had taken place. The deformed portion of the rock can be at once distinguished by its turbid appearance, differing in a marked manner from the clear transparent mosaic of the

unaltered cone. This turbid appearance is most marked along a series of reticulating lines running through the sections, which when highly magnified are seen to consist of lines or bands of minute calcite granules. They are lines along which shearing has taken place. The calcite individuals along these lines have broken down, and the fragments so produced have moved over and past one another, and remain as a compact mass after the movement ceased. In this granulated material are enclosed great numbers of irregular fragments and shreds of calcite crystals, bent and twisted, which have been carried along in the moving mass of granulated calcite as the shearing progressed. This structure is therefore cataclastic, and is identical with that seen in the felspars of many gneisses.

Between these lines of granulated material the marble shows movements of another sort. Most of the calcite individuals in these positions can be seen to have been squeezed against one another and in many cases a distinct flattening of the grains has resulted, with marked strain shadows, indicating that they have been bent or twisted. They show, moreover, a finely fibrous structure in most cases, which, when highly magnified, is seen to be due to an extremely minute polysynthetic twinning. The chalky aspect of the deformed rock is in fact due chiefly to the destruction by this repeated twinning of the continuity of the cleavage surfaces of the calcite individuals, thus making the reflecting surfaces smaller. By this twinning, the calcite individuals are enabled under the pressure to alter their shape somewhat, while the flattening of the grains is evidently due to movements along the gliding planes of the crystals. In these parts, therefore, the rock presents a continuous mosaic of somewhat flattened grains.

From a study of the thin sections it seems probable that very rapid deformation tends to increase the relative abundance of the granulated material, and in this way to make the rock weaker than when the deformation is slow.

When the marble is heated to 300° C. in a suitably-constructed apparatus and is then subjected to deformation under conditions which otherwise are the same as before, the cataclastic structure is found to be absent and the strength of the deformed marble rises to 10,652 lbs. to the square inch, that is to say, it is nearly as strong as the original rock. The calcite grains, which in the original rock are practically equidimensional, are now distinctly flattened, some of them being three or even four times as long as they are wide. Some grains can be seen to have been bent around others adjacent to them, the twin lamellæ curving with the twisted grain. In others again of these twisted lamellæ, the twinning only extends to a certain distance from the margin, leaving a clear untwinned portion in the centre. The rock consists of a uniform mosaic of deformed calcite individuals.

When the deformation is carried out at 400° C., no trace of cataclastic structure is seen.

An experiment was then made in which the marble was deformed at 300° C., but in the presence of moisture, water being forced through the rock under a pressure of 460 lbs. per square inch during the deformation, which extended over a period of fifty-four days, or nearly two months. Under these conditions the marble yielded in the same manner as when deformed at 300° C., in the absence of moisture, that is, by movements on gliding planes and by twinning, but without cataclastic action. The deformed marble, however, when tested in compression, was found actually to be slightly stronger than a piece of the original marble of the same shape. The structure developed was identical with that of the marble deformed at 300° C. in the absence of water. The presence of water, therefore, did not influence the character of the deformation. It is quite possible, however, that there may have been a deposition, of infinitesimal amount, of calcium carbonate along very minute cracks or fissures, which thus helped to maintain the strength of the rock. No signs of such deposition, however, were visible.

By studying the marble deformed at a temperature of 300° C., or better at 400° C., it will be seen that structures induced in it by the movements, and the nature of the motion, are precisely the same as those observed in metals when they are deformed by impact or by compression. In a recent paper by Messrs. Ewing and Rosenhain, "Experiments in Micro-metallurgy: Effects of Strain," which appeared in these Proceedings, three photographs of the same surface of soft iron, showing the results of progressive deformation under pressure, are shown, which photographs could not be distinguished from those of thin sections of the marble described in the present paper, at corresponding stages of deformation. In both cases the movements are caused by the constituent crystalline individuals sliding upon their gliding planes or by polysynthetic twinning. In both cases the motion is facilitated by the application of heat. The agreement between the two is so close that the term "flow" is just as correctly applied to the movement of the marble in compression under the conditions described, as it is to the movement which takes place in gold when a button of that metal is squeezed flat in a vice, or in iron when a billet is passed between rolls.

In order to ascertain whether the structures exhibited by the deformed marble were those possessed by the limestones and marbles of contorted districts of the earth's crust, a series of forty-two specimens of limestones and marbles from such districts in various parts of the world were selected and carefully studied. Of these, sixteen were found to exhibit the structures seen in the artificially-deformed marble. In these cases the movements had been identical with those developed

in the Carrara marble. In six other cases the structures bore certain analogies to those in the deformed rock but were of doubtful origin, while in the remaining twenty the structure was different.

The following is a summary of the results arrived at:—

1. By submitting limestone or marble to differential pressures exceeding the elastic limit of the rock and under the conditions described in this paper, permanent deformation can be produced.

2. This deformation, when carried out at ordinary temperatures, is due in part to a cataclastic structure and in part to twinning and gliding movements in the individual crystals comprising the rock.

3. Both of these structures are seen in contorted limestones and marbles in nature.

4. When the deformation is carried out at 300° C., or better at 400° C., the cataclastic structure is not developed, and the whole movement is due to changes in the shape of the component calcite crystals by twinning and gliding.

5. This latter movement is identical with that produced in metals by squeezing or hammering, a movement which in metals, as a general rule, as in marble, is facilitated by increase of temperature.

6. There is therefore a flow of marble just as there is a flow of metals, under suitable conditions of pressure.

7. The movement is also identical with that seen in glacial ice, although in the latter case the movement may not be entirely of this character.

8. In these experiments the presence of water was not observed to exert any influence.

9. It is believed, from the results of other experiments now being carried out but not yet completed, that similar movements can, to a certain extent at least, be induced in granite and other harder crystalline rocks.

"Lines of Induction in a Magnetic Field." By H. S. Hele-Shaw, F.R.S., and A. Hay, B.Sc.

Received June 13,—Read June 21, 1900.

(Abstract.)

When a viscous liquid flows in a thin layer between close parallel walls, the motion takes place along stream-lines identical with those of a perfect liquid. The course of the stream-lines may be rendered evident by injecting into the clear liquid thin bands of coloured liquid.

If the thickness of the liquid layer be varied, then there will be a decrease of resistance to the flow wherever there is an increase of